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CHARACTERISTICS OF FIXED-DISPERSION CONE VALUES

By Rex A. Elder, A. M. ASCE, and Gale B. Dougherty, J. M. ASCE

HYDRAULICS DIVISION

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PAPERS

CHARACTERISTICS OF FIXED-DISPERSION CONE VALVES

By Rex A. Elder,[1] A. M. ASCE, and Gale B. Dougherty,[2] J. M. ASCE

Synopsis

The Tennessee Valley Authority (TVA) has installed and operated five fixed-dispersion cone valves at the Chatuge, Fontana, Nottely, and Watauga projects. The hydraulic laboratory of the TVA has been closely associated with the design of the dissipating structures which were placed around these valves (known as "Howell-Bunger" valves) and has therefore made prototype observations of their performance. The Fontana and Watauga installations were made in enclosed conduits so that all air drawn into the valve area must be supplied through long air passages. Although the air demand is a function of the structure surrounding the valve, observations have been made at these installations to yield an indication of the air demand conditions. Correlation of the observations of operation of the dissipating structures and the air demand quantities have led to the formulation of ideas as to the mechanics of the air demand.

In addition to the prototype observation studies made by the hydraulic laboratory, the staff was also delegated to prepare accurate ratings of these valves for use in operating them as integrated parts of the TVA multipurpose water system. These valves were rated by field measurement of the discharge, and of the differential pressures in the conduit upstream from the valve. Sufficient data were obtained, also, to allow calculation of the discharge coefficients. These tests were run on valves with diameters of 78 in., 84 in., and 96 in., and covered gross heads from 26 ft to 296 ft.

Introduction

Essentially the valve analyzed in this paper is a cylindrical gate mounted with the axis horizontal. When open, the flow is deflected by a conical end

Note.—Written comments are invited for publication; the last discussion should be submitted by March 1, 1953.

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piece mounted with the apex upstream and issues from the valve as a diverging hollow conical jet. Fig. 1 shows a typical valve and valve installation. The deflector cone is connected to the valve body by vanes that connect the two parts and act as guides to the external sleeve. The external sleeve, which controls the valve opening, seats against the cone and retracts over the outside of the valve body. The sleeve is moved by means of screws, connected by shafting and gearing to the operating motor and controls. The position of this sleeve is shown on an indicator dial which is directly connected to the driving mechanism. With the dial properly graduated and calibrated, the valve can be set readily and accurately to any desired discharge. Since the sleeve does not operate against water pressure, the force required to open or close the valve is only that necessary to overcome the frictional resistances of

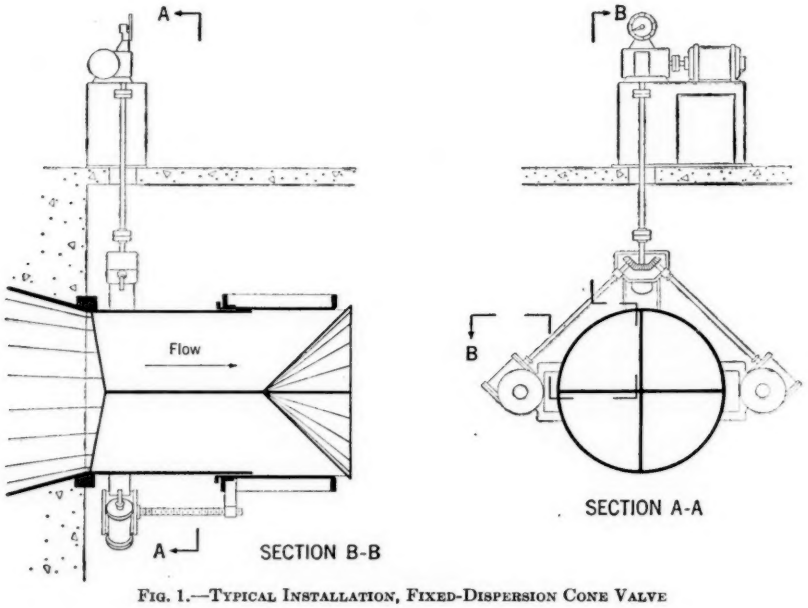
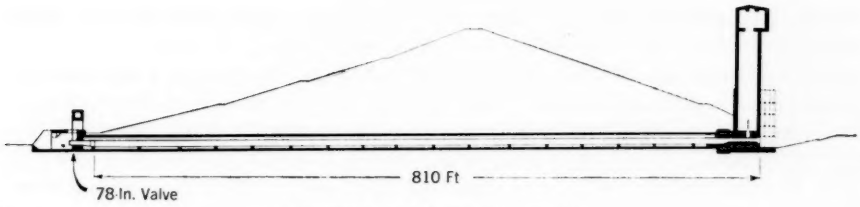


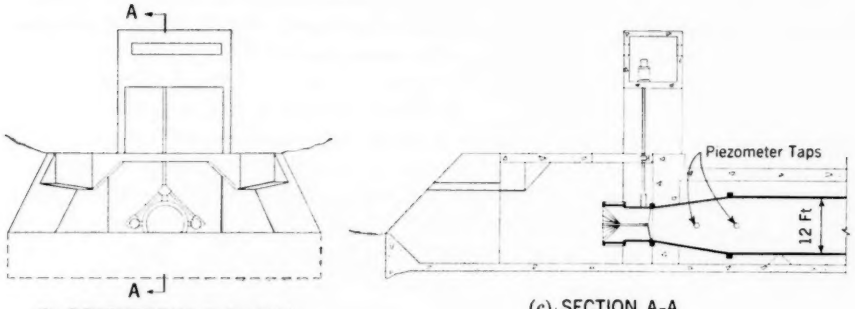
FIG. 1.—TYPICAL INSTALLATION, FIXED-DISPERSION CONE VALVE

the sleeves and gearing. Thus, the motive force is a constant for the entire range of sleeve movement.

TVA Installations.—Fixed-dispersion cone valves have been installed at the Chatuge, Nottely, Fontana, and Watauga projects of the TVA. The major features of the Chatuge installation are shown in Fig. 2. The valve is 78 in. in diameter and is located at the end of a 12-ft-diameter steel conduit 769.5 ft long. The valve discharges into an open-type energy dissipating structure. Two rings of piezometers are provided in the transition section immediately upstream from the valve for flow metering purposes. This valve operates between heads of 59 ft and 128 ft with a maximum expected head of 133.3 ft. The Chatuge Reservoir stores water during the wet season and releases it through the valve during low-water periods. The project was

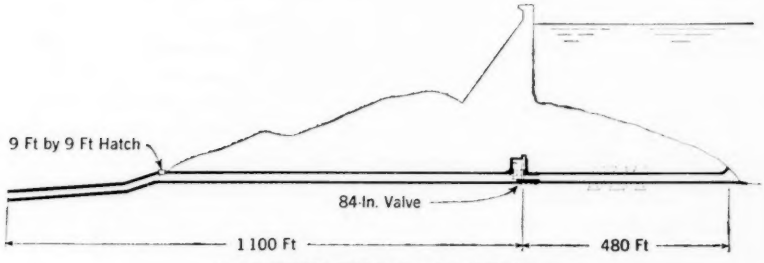


(*a*) SECTION THROUGH SLUICEWAY

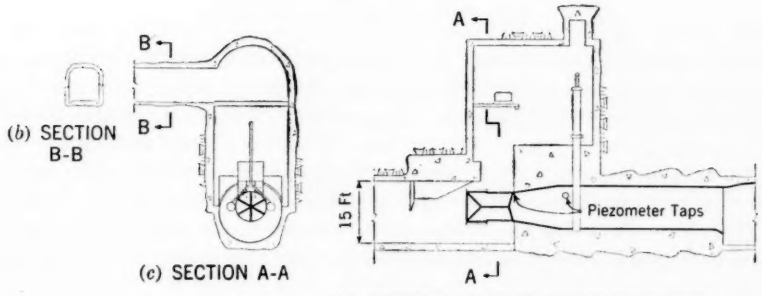


(*b*) DOWNSTREAM ELEVATION (*c*) SECTION A-A

FIG. 2.—VALVE INSTALLATION, CHATUGE PROJECT



(*a*) SECTION THROUGH SLUICEWAY



(*b*) SECTION B-B (*c*) SECTION A-A (*d*) SECTION THROUGH VALVE CHAMBER

FIG. 3.—VALVE INSTALLATION, FONTANA PROJECT

put in operation in 1943 and discharges have been made through the valve on an average of 223 days of each year since that date.

The Nottely installation is nearly identical in design and purpose with that at Chatuge except that the conduit is a pressure tunnel with the upstream 364 ft being 15 ft in diameter and concrete-lined, and the downstream 374 ft, 12 ft in diameter, and steel-lined. The normal head range on the valve is from 20 ft to 160 ft with a maximum expected head of 167.9 ft. This project was put in operation in 1943 and dicharges have been made through the valve on an average of 162 days of each year since that date.

The Fontana valve is 84 in. in diameter and is located in a gallery beneath the right abutment of the dam as shown in Fig. 3. The valve discharges

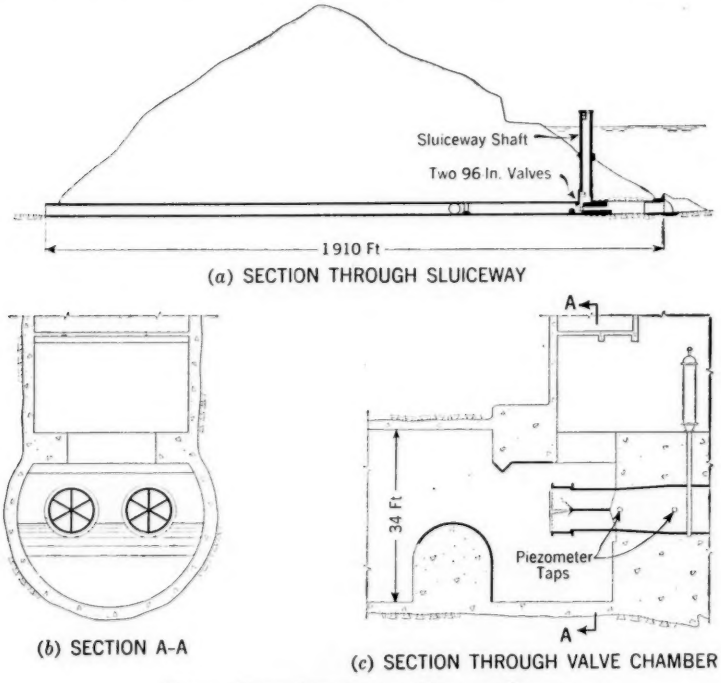


FIG. 4.—VALVE INSTALLATION, WATAUGA PROJECT

into a 15-ft concrete-lined tunnel in which special dissipating structures are built. All air is supplied to the valve through the access gallery and one 36-in. vent drilled vertically to the surface. No provisions are made for metering the flow. A single piezometer was placed in the valve body for test purposes. This valve was installed for regulating purposes during the final stages of the project construction and for extreme low-water releases after completion of construction. Therefore, the valve has been operated under heads from 26 ft to 346 ft. The maximum possible head would be 382.1 ft with a maximum operating head of 373 ft.

The Watauga installation consists of two 96-in. valves located in a tunnel, 34 ft in diameter, beneath the right abutment of the dam. Special dissipating

structures, shown in Fig. 4, are built into the tunnel. All air is supplied through the vertical access tower (diameter, 25 ft) located directly over the valves. Two rings of piezometers are installed in the rectangular section upstream from the valves for flow metering purposes. These valves are installed for reservoir regulation purposes and are operated between heads of 109 ft and 253 ft with a maximum of 275.4 ft. To date (1952) they have not been operated except for test purposes.

Discharge Characteristics

The integrated multipurpose operation of a large number of projects makes accurate ratings for the various hydraulic structures a necessity. Accurate ratings for large, fixed-dispersion cone valves at all sleeve positions were unavailable when the first TVA valves were put into operation. A program was initiated, therefore, to obtain such ratings.

The rating of large hydraulic valves is usually difficult if for no other reason than the magnitude of the water that they discharge. In the case of the tests presented in this paper all the valves had to be rated with a minimum use of water as it was impractical to schedule the ratings for periods of high releases. Thus, a method was sought that would give sufficient data to define the rating accurately at all sleeve positions and would still keep the quantity of water discharged at a minimum.

At all installations a means was found for measuring, in the conduit immediately upstream from the valve, a differential pressure proportional to the discharge. These differential pressures could be measured quickly with only a small usage of water and thus a value, proportional to the discharge, for a large number of sleeve positions could be readily determined. In addition to the differential pressures, the hydraulic grade-line elevation could be obtained by measuring the pressure at a piezometer at or near the base of the valve. All installations were at operating projects which had permanently installed headwater recorders so that gross heads were also available.

With these data and one or more discharge measurements taken at any gate position and headwater elevation a rating can be determined. Assuming that the flow in the conduit is near or in the fully turbulent region, the discharge (in cubic feet per second) through the valve may be expressed as

$$Q = C_G A \sqrt{2 g H_G} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which C_G is a constant for any sleeve position; A is the flow area of the valve in square feet; g is the acceleration of gravity in feet per second per second; and H_G is the gross head on the valve in feet. Since A and g are constants for any given valve and C_G is a constant for any given sleeve position, transposition of the terms to—

$$\frac{Q}{\sqrt{H_G}} = C_G A \sqrt{2 g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2a)$$

—gives an equation which has the variables on the left and a constant, f, for each sleeve position on the right, thus:

$$\frac{Q}{\sqrt{H_G}} = f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2b)$$

Assuming that fully developed turbulent flow exists in the conduit leading to the valve, the discharge may be expressed as

$$Q = K\sqrt{\Delta P} \quad \ldots\ldots (3)$$

in which ΔP is the pressure difference between two points in the conduit expressed in feet of water and K is a constant for the particular conduit. Combining Eqs. 1 and 3 the equation—

$$C_G A \sqrt{2gH_G} = K\sqrt{\Delta P} \quad \ldots\ldots (4)$$

—will result, from which by transposition,

$$K\sqrt{\frac{\Delta P}{H_G}} = C_G A \sqrt{2g} \quad \ldots\ldots (5)$$

As the right-hand terms of Eqs. 2*a* and 5 are identical,

$$\frac{Q}{\sqrt{H_G}} = K\sqrt{\frac{\Delta P}{H_G}} \quad \ldots\ldots (6)$$

Since in Eq. 2*b* $\frac{Q}{\sqrt{H_G}}$ is a function of the sleeve position, the quantity $\sqrt{\frac{\Delta P}{H_G}}$ in Eq. 6 must also be a function of a sleeve position with the numerical values differing by the factor K. Thus, a semi-log plotting of $\sqrt{\frac{\Delta P}{H_G}}$ versus sleeve position will give a curve of the same shape as the curve of a semi-log plotting of $\frac{Q}{\sqrt{H_G}}$ versus sleeve position. Since values of ΔP and H_G were readily obtainable for each sleeve position, the shape of the curve would be established. With one or more points on the $\frac{Q}{\sqrt{H_G}}$-curve, the entire curve could then be drawn by fitting the $\sqrt{\frac{\Delta P}{H_G}}$-curve through these points. Actually, in practice, the plots were made as $\frac{\Delta P}{H_G}$ versus sleeve position and $\frac{Q^2}{H_G}$ versus sleeve position because of the ease of computing these values. Since the semi-logarithmic plot was used, the computation of the square of both log terms was permissible.

The definition of the curve for $\frac{Q}{\sqrt{H_G}}$ versus sleeve position is all that is required to rate any given valve installation. However, for future design purposes and for comparison of results from the several valves tested, the discharge coefficient is desirable.

The discharge coefficient for a fixed-dispersion cone valve can be defined in terms of net head at the base of the valve and an area which, for the purposes defined herein, can be taken as the net flow area in the valve body, thus:

$$C = \frac{Q}{A\sqrt{2gH}} \quad \ldots\ldots (7)$$

in which C is the coefficient of discharge for a given sleeve position and H is the net head at the base of the valve.

The flow Q could be determined from the curves of $\frac{Q}{\sqrt{H_G}}$ versus sleeve position, and the area A was obtained by actual measurement of the valve; H, however, could not be measured directly in the field but could be computed since the pressure head at or near the base of the valve was obtained by field measurement and the velocity head could be computed after the discharge was determined.

Rating of the Fontana Valve.—The application of these methods can be illustrated best by describing the Fontana rating. To obtain the discharge rating, only the differential pressures between two points in the closed conduit above the valve for known sleeve position and headwater elevations, and one or more discharge measurements for known sleeve positions and headwater elevations, were required. The computation of the discharge coefficient required, in addition, the measurement of the pressure head at or near the base of the valve, the area of the conduit at the point of pressure head measurement, and the measurement of the flow area in the valve body.

Differential Pressures.—The differential pressures were measured between the downstream end of a 3-in. by-pass line around the vertical slide gate, which is just upstream from the valve, and a piezometer which was drilled into the body of the valve. The connection to the downstream side of the by-pass line could be readily made in the valve chamber, as a flushing arrangement which opened into the valve chamber had been provided in the piping. The piezometer in the valve body was specially placed for these tests.

The range of heads tested and the type of equipment available at the laboratory at the time of the various tests were such that no set method was used in making these measurements. Six series of tests were made with one or more of the following methods being used during each test:

1. Measurement of the hydraulic grade-line pressure with water, mercury, and bourdon gages, and a special electrical recorder which used a bourdon tube pickup. The differentials were then determined by taking the difference in hydraulic grade-line elevations.
2. Measurement of the differential pressures by air-water or water-mercury differential gages and by the special electrical recorder with a differential bellows-type pickup.

Sleeve Positions.—For rating purposes, the sleeve position as given by the indicator dial on the driving mechanism was all that was required. The indicator dial was divided into one hundred divisions. The pointer was fairly rough but the divisions were large enough in comparison with the pointer to make the estimation of 0.1-division positions possible. The indicator read 0.75 when the sleeve was closed and 98.5 when opened as far as the limit switches would allow. For comparison of the results with other valves, the actual sleeve travel was necessary. The travel was measured with a steel tape, and a comparison between indicated sleeve position and the actual travel thus determined.

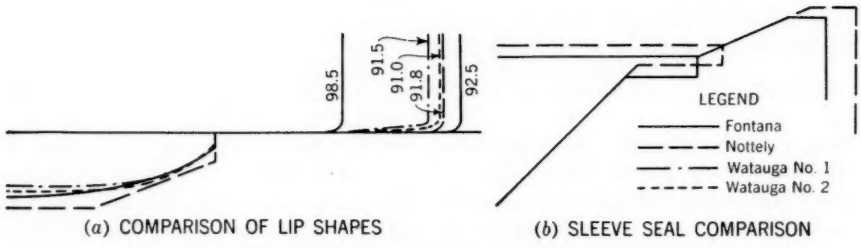


FIG. 5.—COMPARISON OF FLOW AREAS, FIXED-DISPERSION CONE VALVES

Headwater Elevation.—The headwater elevations were obtained from the chart of the water-stage recorder near the center of the dam. The instrument was checked against the actual water surface after each test and the error, if any, was subsequently removed from the data.

Discharge Measurements.—Opportunities for making field measurements of discharge were infrequent because of the necessity for generating power as a war emergency measure and the fact that the valve discharge could not be separated from the turbine discharge in the river below. Five tests were made during periods when the turbines were shut down and sufficient time and water were available to allow the river flow to stabilize before the measure-

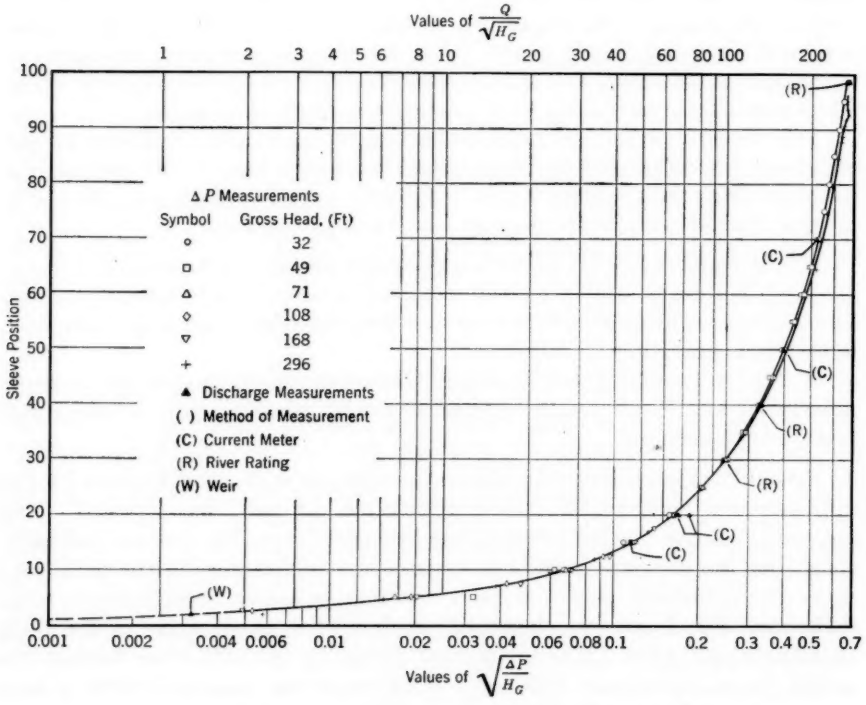


FIG. 6.—SLEEVE POSITION IN RELATION TO $\sqrt{\frac{\Delta P}{H_G}}$ AND $\frac{Q}{\sqrt{H_G}}$ AT FONTANA DAM

ments were started. The discharges for these tests were obtained from current meter measurements made in the river channel. These measurements were made by personnel of the United States Geological Survey (USGS) with selected meters and using the best techniques known for this type of measurement.

Six discharge values were obtained from a stage-discharge curve that had been prepared by the USGS for a temporary channel through the construction area. These values were taken for periods when the turbines were not discharging and when the valve was held at a constant discharge for sufficient time for the stage to stabilize. One extremely low discharge measurement was made by calculating the flow over the weir on the outlet structure.

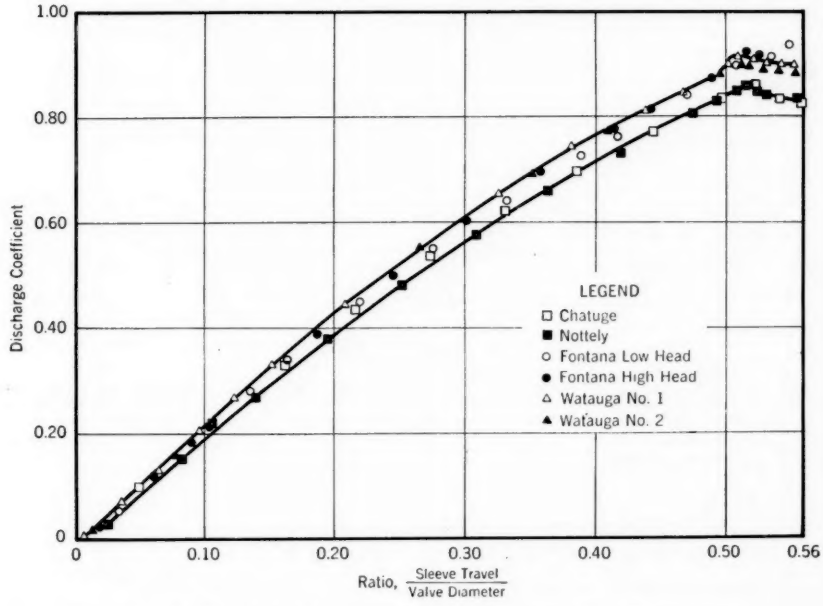
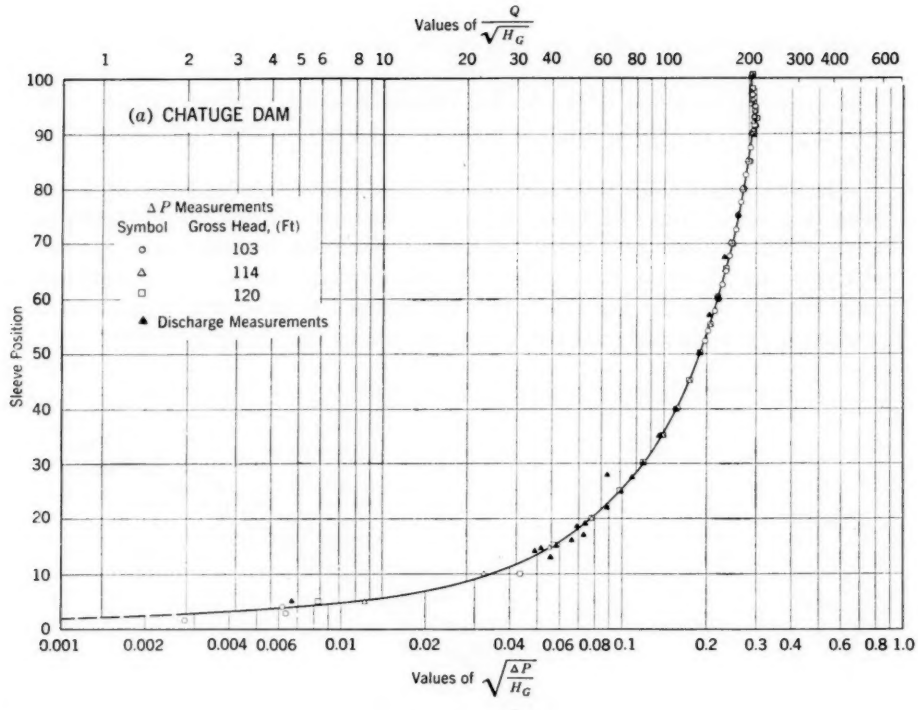


FIG 7.—DISCHARGE COEFFICIENTS, FIXED-DISPERSION CONE VALVES

Pressure Head.—The pressure head was measured at the base of the valve by use of the special piezometer placed there for differential pressure measuring purposes. The pressures were obtained by water, mercury, or bourdon gages, or by a special electrical recorder which used a bourdon-type pickup.

Flow Area of Body.—On the Fontana project there was a difference between the flow area of the body and the area at the point of pressure head measurement. The actual dimensions of the valve necessary for computing this area were obtained by field measurement. The shape of the outlet end of the body and the seal area of the cone were also determined (Fig. 5).

Test Procedure.—In general, the test procedure was to set the valve sleeve at about ten different positions during the opening cycle and then to set positions midway between each of these on the closing cycle. If any


Values of $\frac{Q}{\sqrt{H_G}}$
1 2 3 4 5 6 8 10 20 30 40 60 80 100 200 300 400 600
(a) CHATUGE DAM
Δ P Measurements
Symbol Gross Head, (Ft)
103
114
120
Discharge Measurements
Sleeve Position
0 10 20 30 40 50 60 70 80 90 100
0.001 0.002 0.004 0.006 0.01 0.02 0.04 0.06 0.08 0.1 0.2 0.3 0.4 0.6 0.8 1.0
Values of $\sqrt{\frac{\Delta P}{H_G}}$

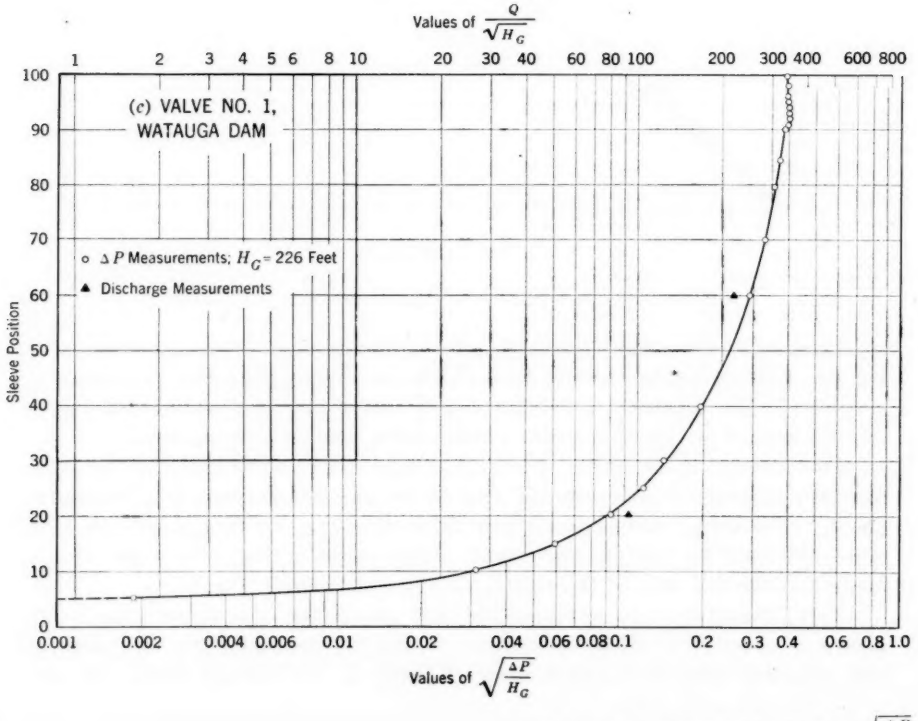
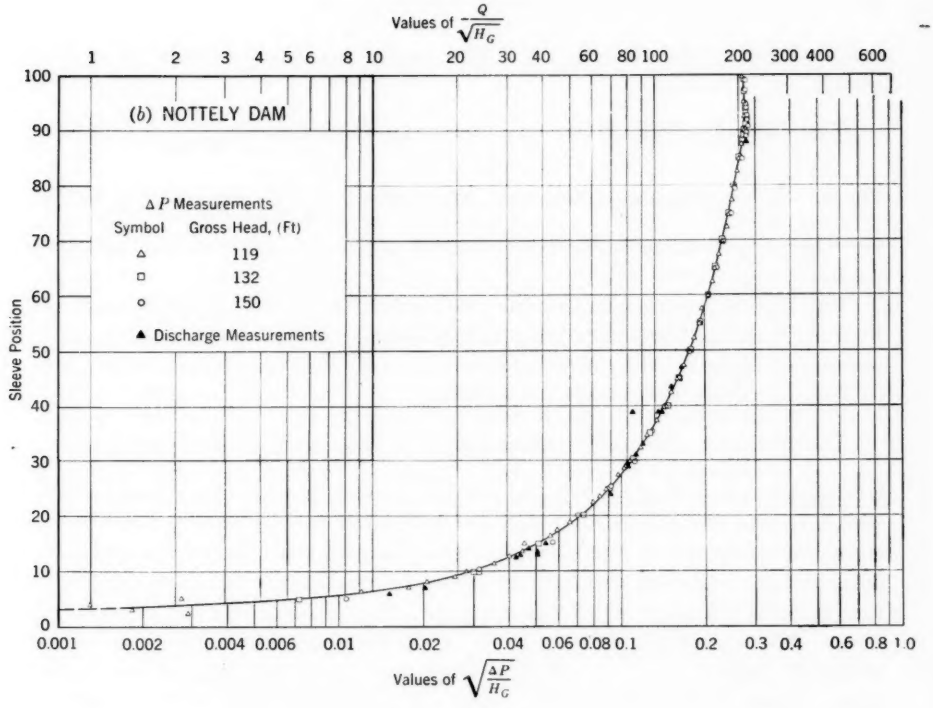
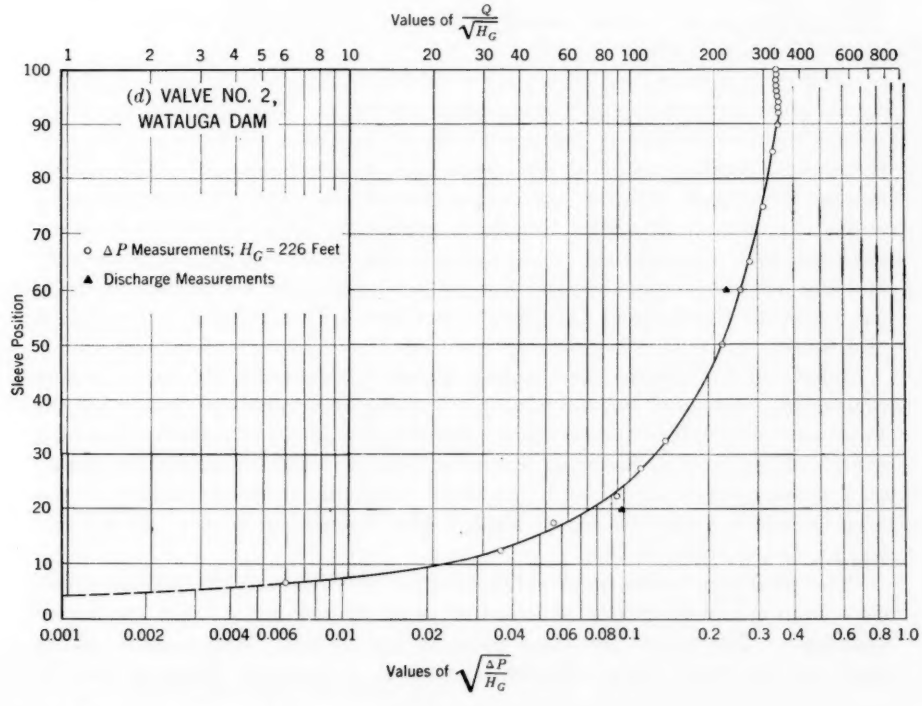

Values of $\frac{Q}{\sqrt{H_G}}$
1 2 3 4 5 6 8 10 20 30 40 60 80 100 200 300 400 600 800
(c) VALVE NO. 1, WATAUGA DAM
Δ P Measurements; H_G = 226 Feet
Discharge Measurements
Sleeve Position
0 10 20 30 40 50 60 70 80 90 100
0.001 0.002 0.004 0.006 0.01 0.02 0.04 0.06 0.08 0.1 0.2 0.3 0.4 0.6 0.8 1.0
Values of $\sqrt{\frac{\Delta P}{H_G}}$

FIG. 8.—SLEEVE POSITION IN RELATION TO $\sqrt{\frac{\Delta P}{H_G}}$


Values of $\frac{Q}{\sqrt{H_G}}$
1 2 3 4 5 6 8 10 20 30 40 60 80 100 200 300 400 600
(b) NOTTELY DAM
Δ P Measurements
Symbol Gross Head, (Ft)
△ 119
□ 132
○ 150
▲ Discharge Measurements
Sleeve Position
0 10 20 30 40 50 60 70 80 90 100
0.001 0.002 0.004 0.006 0.01 0.02 0.04 0.06 0.08 0.1 0.2 0.3 0.4 0.6 0.8 1.0
Values of $\sqrt{\frac{\Delta P}{H_G}}$


Values of $\frac{Q}{\sqrt{H_G}}$
1 2 3 4 5 6 8 10 20 30 40 60 80 100 200 300 400 600 800
(d) VALVE NO. 2,
WATAUGA DAM
○ Δ P Measurements; H_G = 226 Feet
▲ Discharge Measurements
Sleeve Position
0 10 20 30 40 50 60 70 80 90 100
0.001 0.002 0.004 0.006 0.01 0.02 0.04 0.06 0.08 0.1 0.2 0.3 0.4 0.6 0.8 1.0
Values of $\sqrt{\frac{\Delta P}{H_G}}$

AND $\frac{Q}{\sqrt{H_G}}$, FIXED-DISPERSION CONE VALVES

definite breaks were noticed in the data, additional points were taken in that range.

Tests Results.—The differential pressure data plotted as $\sqrt{\frac{\Delta P}{H_G}}$ are given in Fig. 6. The experimental discharge data plotted as $\sqrt{\frac{Q}{H_G}}$ are also given in Fig. 6. The method of measurement is given by the letters appended to the plotted points.

Fig. 7 gives the discharge coefficients for the 32.0-ft and 295.8-ft gross-head Fontana tests and for all the other valves tested. Only the two Fontana tests were used, as the other tests did not contain a sufficient range of sleeve positions to make the computation of C practicable.

The C-values and $\sqrt{\frac{\Delta P}{H_G}}$-values shown in Figs. 6 and 7 for the 32.0-ft and 295.8-ft gross-head tests do not plot along the same curve, as should be expected. The data give some indication that the ΔP-values for the 295.8-ft test are too large, probably due to the somewhat poor location and size of the upstream piezometer. Sufficient data are not available to establish this point definitely; therefore, the data reduction has been carried through using the test values in all cases. The maximum spread in the coefficient curves for these two tests is slightly more than 2%, with the larger discharge coefficient for the higher head. None of the tests on the other valves covered such a wide range of heads; therefore, no conclusions can be drawn from these tests to aid in evaluating the Fontana results.

The lack of fit at the largest sleeve positions is caused by loss of control by the sleeve, which occurs at the higher velocities. The approximate outlet velocity for the 98.5 sleeve position at the 32-ft head is 40 ft per sec, whereas that for the same position at the 296-ft head is 120 ft per sec. With such a marked increase in velocity, the contraction at the higher velocity is considerably larger and, therefore, the sleeve cannot be retracted as far before it loses control. Fig. 5(*a*) shows the shape of the outlet end of the valve body and the position of the sleeve at the point at which the control shifted from the sleeve to the body at the 296-ft head test. The 98.5-sleeve position is also shown.

Rating of the Chatuge and Nottely Valves.—Essentially the same testing procedures were used for the Chatuge and Nottely valves as were used for Fontana. The differential pressures were obtained from two piezometers which were installed for flow metering purposes (Fig. 2). The Chatuge valve closed at a sleeve position of 0.7 and was at its maximum position allowed by the limit switch at a dial reading of 100.5. The Nottely valve closed at 0.9 and was at its maximum at 99.6.

The discharge values were obtained from well-defined river ratings which have been established over a period of years by standard USGS measuring principles. The valves for these projects are used for long periods during each year so that a large number of periods of constant discharge can be

found in the records. These data, in the form of $\frac{Q}{\sqrt{H_G}}$-points and the $\sqrt{\frac{\Delta P}{H_G}}$-points, are plotted in Figs. 8(*a*) and 8(*b*) for Chatuge and Nottely, respectively.

The pressure head was measured at the upstream piezometer. Therefore, the pressure head at the base of the valve for use in the coefficient determination was computed by reducing the measured pressure head by the difference in the velocity heads at the two sections, and a friction loss was computed by Manning's equation using an n-value of 0.011. Average values of the hydraulic radius and velocity were used. No allowance was made for the contraction losses, if any. The friction loss correction was almost negligible, being equal to less than 0.3%. The discharge coefficient values are plotted in Fig. 7.

Rating of the Watauga Valve.—The Watauga valves were rated by essentially the same means as those at Fontana. The differential pressures were taken from two rings of piezometers located in the transition section immediately upstream from the valve (Fig. 4). The $\sqrt{\frac{\Delta P}{H_G}}$-values are plotted in Figs. 8(*c*) and 8(*d*). The valves closed at a sleeve position of 3.0 and were tested to positions above 100 as the limit switches had not been installed at the time of the tests. Since the tests were made (1950), the limit switches have been set at the 92 position so that "overgating" of the valve could not occur.

These two valves are used for any reservoir regulation which cannot be supplied by the turbines. Since 1949, when the valves were placed in operation, the water supply has been such that valve regulation has not been required. Therefore, the ratings have had to be made with but one discharge measurement for each valve. These two measurements had to be made at a river section that contained the combined valve and turbine discharge and which was affected by the backwater from Wilbur Dam in North Carolina. Since Wilbur Lake contains only 72 acres, it was impossible to hold the pool at a constant level during the discharge period. Because the Watauga turbines were not rated at the time of these measurements, two discharge measurements had to be made for each test, the first with the turbine and valve and the second with the turbine alone. As a consequence of the poor measuring conditions, the ratings for these valves can be considered as preliminary only, and the data are included in this report solely to extend the range of valve sizes tested. Although the accuracy of the data is not comparable with that for the Fontana, Nottely, and Chatuge valves, the observations should be usable for design purposes and will give a close approximation for valves that cannot be rated easily. The $\sqrt{\frac{\Delta P}{H_G}}$-values for both valves were combined into a single curve, which was then fitted to the two $\frac{Q}{\sqrt{H_G}}$-values. The $\sqrt{\frac{\Delta P}{H_G}}$-values for each valve have been plotted separately in Figs. 8(*c*) and 8(*d*) merely for simplification of the plots.

The pressure head was measured at the downstream piezometer, which is located 8 in. upstream from the base of the valve. The pressure head at the base of the valve was computed by subtracting the difference in velocity heads at the two sections from the measured value. Because of the short length between sections no allowance was made for friction or other losses. The discharge coefficients are plotted in Fig. 7.

Comparison of Results.—The results of these discharge rating tests can best be observed in Fig. 7. In general, the coefficient of discharge increases for any given ratio of sleeve travel to body diameter as the body diameter increases. The Fontana data indicate an increase in C with an increase in head but (see under the heading, "Rating of the Fontana Valve; Test Results") this may be explained by possible incorrect differential pressure values.

Each of the valves had a definite break in the curve at a sleeve position of about 90 to 95. This break is caused by the loss of control by the sleeve as it is retracted past a certain position. The point at which this occurs probably is a function of the valve body outlet shape and the velocity of the water through the valve. The Fontana, Nottely, and Watauga valves have been measured. The shapes of the outlet end of the body and the position of the sleeve at the break point in the curve are shown in Fig. 5. Fig. 5(*b*) shows the shape of the seal part of the cone for Fontana and Nottely. Justification of the theory that the velocity of the jet controls the position of sleeve for the break point is shown in Fig. 5(*a*). The slope of a line tangent to the body and to the sleeve, at the position for the break in the curve, increases as the velocity decreases. The Fontana valve, which was tested at a 296-ft gross head, has the flattest slope; the Watauga valves, which were tested at a 226-ft head, have the next flattest slope; the Nottely valve which was tested at heads of from 120 ft to 150 ft was next, and the 32-ft Fontana test did not exhibit a break at the maximum gate position. Naturally a decrease in discharge coefficient means a decrease in discharge; therefore, the maximum discharge for these valves does not necessarily occur at maximum gate position.

Operational Characteristics of Valves.—The TVA has experienced no operational troubles with any of the valves it has in service. They do exhibit two definite characteristics of operation, neither of which is of importance if the valve is operated properly. At settings of 3 to 5 on the dial above the closed position a loud, piercing howl develops. If the valve were to be operated for any length of time at such a position, the noise would be annoying to any personnel close at hand. The existence of the noise indicates a vibration phenomenon that could be harmful to the valve if operated at such a position for extended periods of time. There is some indication that, on the same valve, the noise occurs at smaller openings for low heads than it does for higher heads.

The second operational characteristic of these valves is the vibration that occurs after the break point in the discharge curve is reached. The vibration is worse just beyond the break point and decreases as the sleeve is further retracted. This is undoubtedly explained by a continual shift of control between the sleeve and the body. There is no reason to open the sleeve past the break point. Therefore, once the break point is determined, the limit switches can be set to cut off at that point and this vibration thus cannot occur.

Characteristics of Associated Structures

The associated structures for the fixed-dispersion cone valves used on TVA projects have been built to satisfy two requirements: (1) The energy of the jet must be dissipated sufficiently to prevent channel erosion and to provide for suitable downstream velocities; and (2) the air demand of the valve should be satisfied and kept to a minimum. These requirements have been met in the TVA installations under two different conditions: (*a*) The installation of the valve at the end of a sluice and discharging into the river channel; and (*b*) the installation of the valve in a chamber and discharging into a conduit.

Chatuge and Nottely Projects.—The open discharge type of installation has been used at Chatuge and Nottely dams. The Chatuge installation will be described because the two projects differ in only minor details, and what is true of one is true of the other. Because the valve was placed at a very low level it was necessary to protect the stream channel from erosion at the point of impact of the lower part of the jet. It was also necessary to limit the horizontal spread of the jet and confine it to the stream channel. These requirements were met by combining, into one structure, a short stilling basin to absorb the energy and deflect the lower part of the jet, and a box-type deflector placed downstream from the valve to deflect the diverging jet into the channel. The details of the structure at Chatuge can be seen in Fig. 2. The deflected jet is confined to the stream channel. The operation has been very satisfactory and only minor erosion has occurred downstream from the structure after several years of use. The air required by the jet is drawn through an opening 12 ft by 16 ft directly over the valve. There is a perceptible movement of air toward this opening when the valve is discharging. No measurements of air demand have been made on this installation because of the adequacy of the supply and the difficulty of isolating the flow.

Fontana Project.—An enclosed valve has been used at Fontana, Watauga, and South Holston (in North Carolina). In these installations, air demand was an important consideration in the selection of the type of energy dissipators or velocity reducers to be used.

The 78-in. valve installed at the Fontana project controls the low-level outlet. The valve discharges into a tunnel (diameter, 15 ft) leading to the river channel downstream from the dam. The energy-dissipating structure was required to reduce the downstream velocities and was built as shown in Fig. 3. When the valve is opened the upper part of the jet strikes the roof, is broken up by the two projecting fingers, and is deflected by the wall back onto the tunnel invert. The air required by the jet is drawn through the 8-ft by 8-ft access gallery and an overhead air vent 3 ft in diameter.

Model tests had indicated that slight changes in deflector structures greatly changed the air demand. A model design that produced minimum air demand was developed and used. However, even with a minimum demand, it was recognized that large quantities of air would be required although quantitative values were unobtainable from the model tests. The somewhat oversize access gallery was constructed to meet this anticipated air requirement. Because of the unknown quantitative value, a prototype check program was scheduled

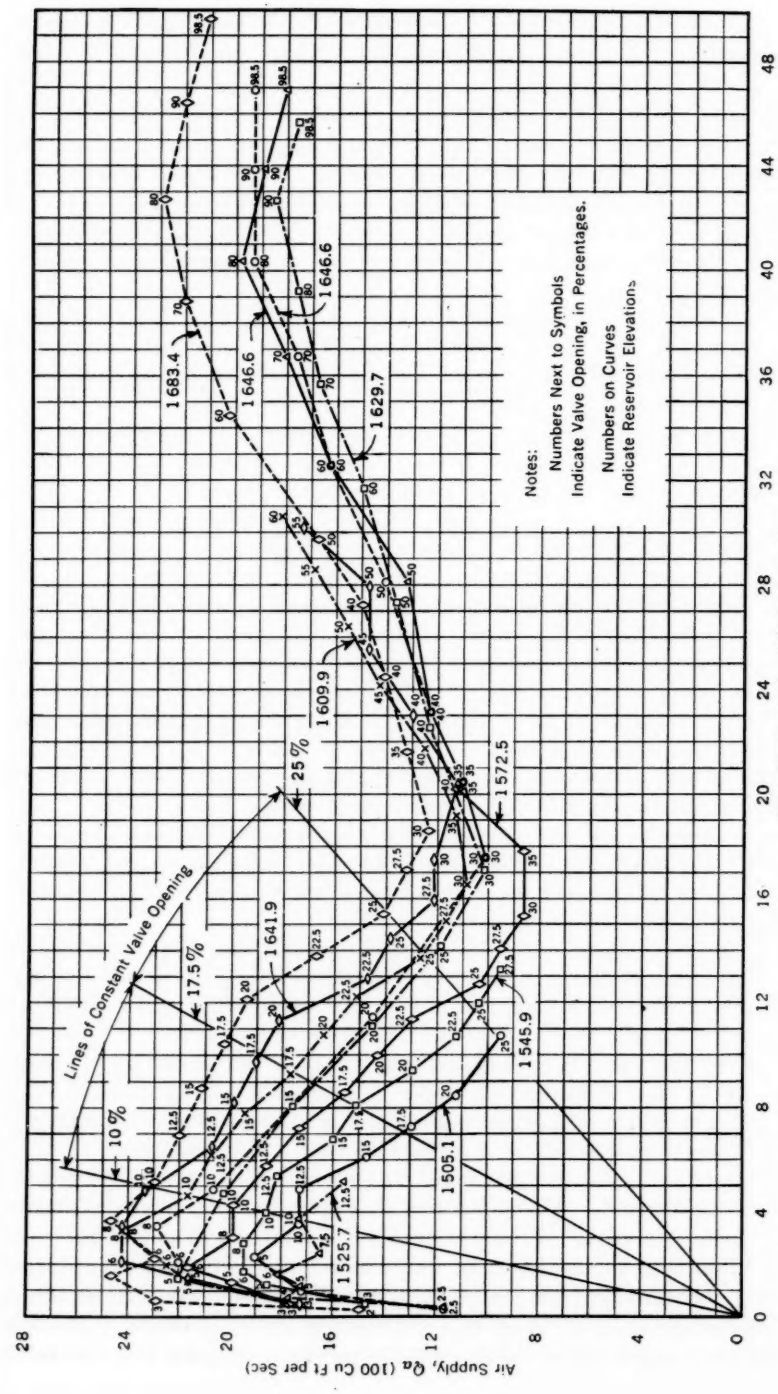


FIG. 9.—PROTOTYPE PERFORMANCE; AIR DEMAND FOR VALVE ON THE FONTANA PROJECT

to determine the air demand for various operating heads and sleeve positions. The air velocity was measured in the 8-ft by 8-ft gallery with an anemometer held at various points in the cross section. The readings were averaged and recorded to the nearest mile per hour. The air supplied by the 3-ft vent could not be measured because of the drip pan installed beneath it, and it could not be plugged because of the inaccessibility of the upper end. Therefore, the data apply only to the air drawn through the gallery. The quantity of air required was computed as the product of measured average wind velocity and the cross-sectional area of the gallery. The gallery is 8 ft by 8 ft with 2-ft fillets in the upper two corners resulting in an area of 60 sq ft. The valve discharge was determined from the valve rating table for the sleeve position

TABLE 1.—AIR-WATER RATIO, FONTANA PROJECT (TVA)

Sleeve Position	GROSS HEAD, H_G, IN FEET										
	168.0	188.6	208.8	235.4	272.8	292.6	304.8	309.5	309.5	346.3	Average
2	...	...	...	...	...	...	...	...	...	62.4	62.4
2.5	43.3	41.7	...	...	...	...	...	...	...	...	42.5
3	...	...	34.2	38.6	36.2	...	33.3	...	...	40.8	36.6
4	...	24.0	...	...	...	...	...	...	...	...	24.0
5	16.0	15.2	15.5	15.7	15.8	15.5	14.9	...	...	15.9	15.56
6	...	11.2	11.4	11.9	11.5	...	11.7	...	10.6	10.4	11.24
7.5	8.39	6.83	...	...	...	...	...	...	...	...	7.61
8	...	...	6.93	6.65	7.53	...	7.13	...	6.66	6.80	6.95
10	4.88	4.60	4.70	4.74	4.78	4.29	4.88	...	4.29	4.50	4.63
12.5	3.58	3.05	3.38	3.26	3.37	...	3.20	...	...	3.17	3.29
15	2.42	...	2.36	2.41	2.52	2.19	2.44	...	...	2.42	2.39
17.5	1.79	...	1.87	1.82	1.92	...	1.95	...	...	1.96	1.885
20	1.338	...	1.383	1.435	1.535	1.308	1.604	...	1.270	1.605	1.435
22.5	...	...	1.053	1.143	1.241	...	1.140	...	...	1.217	1.159
25	0.888	...	0.868	0.818	0.918	0.839	0.959	...	...	0.915	0.887
27.5	...	...	0.720	0.679	0.773	...	0.759	...	...	0.775	0.741
30	...	...	...	0.565	0.656	0.592	0.695	0.576	0.576	0.664	0.618
35	...	...	...	0.486	0.587	...	0.556	0.539	0.539	0.611	0.553
40	...	...	...	0.557	0.578	0.547	0.565	0.533	0.533	0.575	0.555
45	...	...	...	...	0.591	...	0.577	...	...	0.550	0.573
50	...	...	...	...	0.590	0.498	0.527	0.470	0.501	0.563	0.525
55	...	...	...	...	0.591	...	0.574	...	...	...	0.582
60	...	...	...	...	0.594	0.472	...	0.500	0.500	0.588	0.531
70	...	...	...	...	...	0.468	...	0.491	0.480	0.566	0.501
80	...	...	...	...	...	0.448	...	0.490	0.480	0.535	0.488
90	...	...	...	...	...	0.432	...	0.431	0.442	0.473	0.444
98.5	...	...	...	...	...	0.386	...	0.384	0.412	0.425	0.402

at the time of velocity measurement. The air demand versus the water discharge is plotted in Fig. 9. As the valve opened, the air demand increased rapidly to a maximum at a sleeve position of 8. As the sleeve was opened farther, the air demand decreased until a sleeve position of 30 was reached. Beyond this point, the air demand increased slowly but never was as large as it was at sleeve position 8. Fig. 9 indicates that the air demand increased with increased head.

A fairly definite relationship was found for the air-water ratio at each sleeve position for the range of heads tested. Table 1 gives the ratios for each test point and Fig. 10 is a curve based on the average of all test points. From Fig. 10 it will be noted that the air-to-water ratio decreased rapidly until a

sleeve position of 35 was reached, after which little effective change in ratio occurred. To illustrate the magnitude of the air requirement problem, Fig. 11 has been prepared from the curve in Fig. 10. These two curves give the velocity of the air through the access gallery for the maximum demand and for full-valve opening demand.

The model tests proved definitely that the air requirements are a function of the deflector structure design. Therefore the data that have been presented are only applicable for a structure identical to that built at Fontana. The operation of the valve caused water to splash into the rear of the chamber. Splashing began at a sleeve position of about 15. At a sleeve position of 25 the splash reached to the top rear of the operating chamber, a distance of about 45 ft. There was a definite relation between the amount of splashing

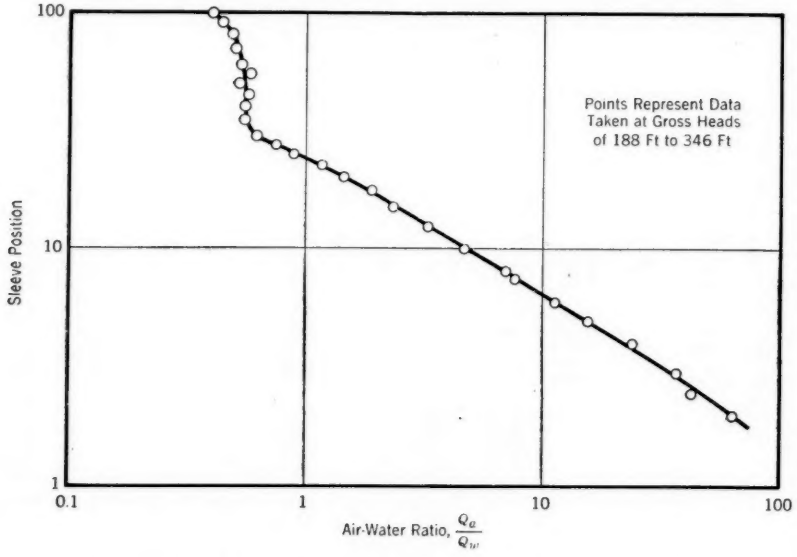


FIG. 10.—SLEEVE POSITION IN RELATION TO $\frac{Q_a}{Q_w}$, FONTANA LOW-LEVEL OUTLET

and the air demand; that is, as the splashing increased the air demand decreased.

Watauga Project.—The two 96-in. valves at Watauga, like Fontana, are built to discharge into a tunnel. The design for this installation was developed by means of model studies (Fig. 4). The two valves are set side by side. A 15-ft-high by 15-ft-thick weir is placed 11.5 ft downstream from the valve to absorb the energy of the lowermost part of the jet. The upper part of the jet strikes the roof deflector and is deflected down beyond the weir. These structures provided proper flow conditions in the tunnel downstream.

The air supply is drawn down the tower through a 10-ft by 12-ft grated opening at the top. Prototype tests to determine the air demanded by this installation were made at the same time as the preliminary rating measurements. Since a very minimum volume of water had been made available for the rating

tests, it was not possible to secure readings at sufficiently close intervals to define the air-demand curves fully or to obtain data for dual valve operation.

The air demand was measured during the rating tests by using the open grate as an orifice. A micrometer, zero-reading, differential manometer was constructed to measure the pressure drop through this grate. The air demand was pulsating; therefore it was necessary to set the micrometer at an average setting. The air volumes were calculated using an orifice coefficient of 0.61 and the net area of the intake opening as 110.3 sq ft (Fig. 12). The air demand for single valve operation reaches a maximum at a sleeve position of 20 and decreases gradually to a maximum valve discharge. The air pulsations are very noticeable, not only because of the rattling of the doors but also because of the aural discomfort to personnel in the shaft. An aneroid barometer placed in the operating chamber pulsated over a range of 0.2 in. of mercury at a frequency of about 50 cycles per min.

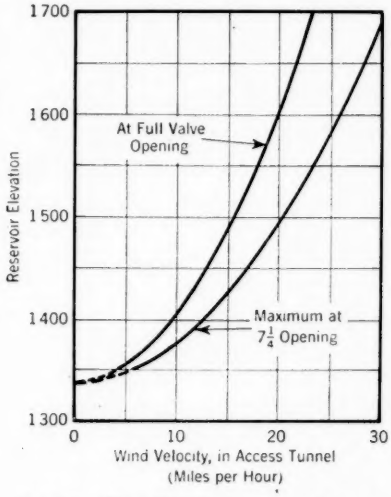


FIG. 11.—WIND VELOCITIES IN THE ACCESS TUNNEL (PROTOTYPE PERFORMANCE), FONTANA PROJECT

As a single valve was opened, splashing over or behind the valves began at about sleeve position 10. The first splashing was in the form of a backward jet of water which was directed across and over the adjacent valve. Further sleeve movement pulled this jet over until it struck the wall between the valves with a sound similar to several rivet hammers. With further opening,

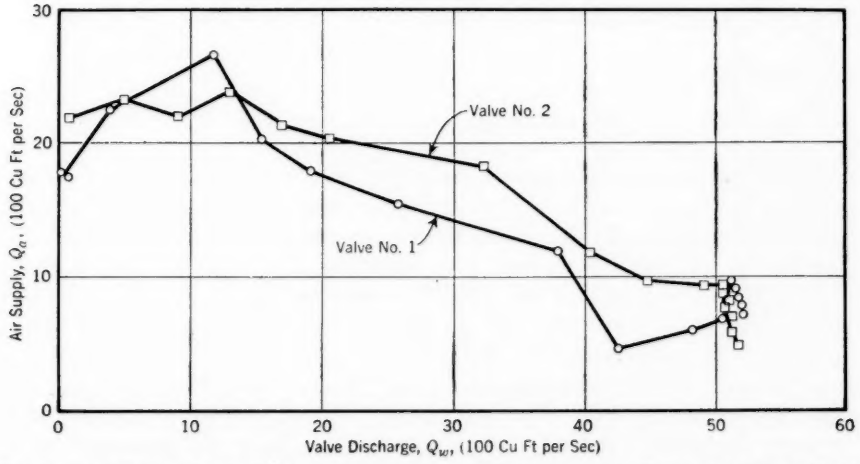


FIG. 12.—AIR DEMAND, FIXED-DISPERSION CONE VALVE AT WATAUGA PROJECT (GROSS HEAD H_G, 226.6 FT)

a swirling motion was imparted to the water which caused it to follow the tunnel walls passing under the valves and splashing it back over the top of them. This splashing finally covered the valves completely. As at Fontana, correlation of the measured air demand and the observed flow conditions indicated that the greater the splash the smaller the air demand would be.

From the tests at Fontana and Watauga the air demand and its variation can be explained as follows. Fig. 13 shows that, as the jet leaves the valve, it is a solid sheet of water of thickness t_1, radius of revolution r_1, and cross-sectional area A_1, in which A_1 is equal to t_1 times $2\pi r_1$. At some distance away the thickness has increased to t_2 due to the expansion of the jet, and the area A_2 has increased materially because of the increase in t and also the

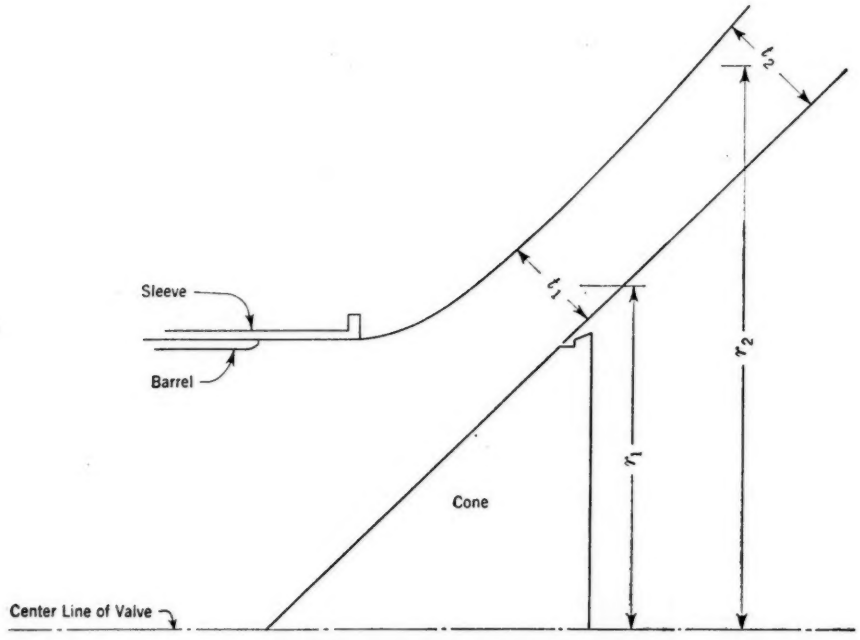


FIG. 13.—DEFINITION SKETCH FOR AIR DEMAND'

increased radius of revolution r_2. Assuming that r_2 is equal to twice r_1, and that $t_1 = t_2$; then $A_2 = 2A_1$. The quantity of water passing each section is the same, and the distance between sections is too short to produce any material decrease in velocity. Therefore, the equations of continuity can be satisfied only by the inflow of air from the surrounding atmosphere. On this basis it can be expected that the air demand will increase with larger sleeve openings. The observed data do not confirm this conclusion but (as has been shown) the visual observations at Fontana and Watauga indicated that the secondary back flow and splash tended to form a curtain that reduced, materially, the flow of air into the jet from the upstream direction. Without a heavy back flow the spray that developed behind the

valves was carried directly into the sides of the discharging water jets. As a curtain of back splash formed, this spray was drawn into any openings in the curtain and directly toward the discharging jets. When (as occurred at Watauga at the higher sleeve positions) the valves were completely smothered, the air demand was reduced to a minimum.

The air data, therefore, can be interpreted as indicating that air requirements greatly in excess of any measured by the TVA can be expected if a curtain of water does not form over the air entrance. It also indicates a possible approach to future designs of low air requirements in which a curtain is deliberately formed. Observations of the results of the action of the back splash on auxiliary equipment placed near the valves and within the path of the spray have indicated that thought must be given to their placement and fastening. Such items as access ladders and grease lines must be fastened very securely to resist the forces exerted upon them by the heavy spray.

Acknowledgments

The fixed-dispersion cone valves which were used in the investigations reported are known as "the Howell-Bunger Valves," developed by C. H. Howell, M. ASCE, and H. P. Bunger, and manufactured by the S. Morgan Smith Company. The investigations of performance were made under the general direction of Albert S. Fry, M. ASCE, and under the immediate direction of the TVA Hydraulic Laboratory staff. G. H. Hickox, M. ASCE, was head of the laboratory during the time when the first measurements on the Fontana, Chatuge, and Nottely valves were being made and was primarily responsible for the methods of analysis used in obtaining the discharge ratings.

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